OCEAN OBSERVING IN THE 4TH DIMENSION – AUTONOMOUS GLIDER SURVEYS IN THE GULF OF MEXICO

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Abstract

The ocean circulation in the Gulf of Mexico is highly dynamic in four dimensions (4D). The circulation varies throughout the interconnected shelf, slope, and deep-ocean (3 dimensions) and varies greatly in time (the 4th dimension). Timely and accurate forecasting of this 4D system remains a challenge for deepwater industry on the outer continental shelf and slope. Long-range autonomous underwater gliding vehicles (AUGVs) enable collection of high spatial resolution data at a very low cost compared to conventional methods. Using these new tools provides a more integrated description of the ocean state and better forecasting. We describe a three-year operational glider program in the Gulf of Mexico. Deployments are generally 120 days, span distances of 2500 km, and collect 1000 CTD profiles to 1000 m. Such surveys span a significant portion of the 8-11 month cycle of Loop Current (LC) growth and eddy detachment. Gliders allow for repeat cross-sections through the LC front, cyclonic frontal eddies, and in close proximity to working platforms in lease areas of the NGOM slope. The in-situ fields of ocean density delineate the subsurface structure of the GOM's dynamic features. Sustained in-situ glider observations throughout the eastern Gulf of Mexico will improve the knowledge and forecasting vital for efficient day-to-day operational management decisions of the offshore petroleum industry.

Introduction

At basin scales, the ocean circulation in the GOM is dominated by the Loop Current. The Loop Current extends northward from the Yucatan Channel into the GOM and connects to the Florida Straits. At times, it extends well north before retroflecting to the southeast and exiting the Gulf. Periodically the LC retroflection will pinch and form a closed recirculation of water that may ultimately detach (or shed) as a Loop Current Eddy (LCE) at intervals from 8-11 months (Forristall, et al., 1992, Leben et al., 2005, Sturges et al., 2005). The LC and LCE are deep structures extending down to nearly 1000 m, and both exhibit strong surface currents in excess of 3.75 knots (2 m/s). The LC and its energetic eddies will, at times, exert a strong influence on the NGOM upper slope and shelf due to the interconnected nature of circulation. A variety of physical mechanisms can potentially influence LC intrusion and eddy separation, including instability of the LC within the GOM and upstream effects propagating though the Yucatan Channel. Loop Current Frontal Eddies (LCFEs) typically form along the western edge of the LC and amplify in an unstable manner as they propagate downstream along the LC (Vukovich and Maul, 1985), exerting a strong influence on the LC position and evolution. These features are difficult to study because of their rapid motion and relatively weak surface thermal signatures and are difficult to track in satellite altimetry due to their small size and the narrowness of altimeter tracks.

Strong ocean currents encountered in any part of the Outer Continental Shelf (OCS) and in deeper waters of the slope can significantly threaten the safe and efficient completion of deepwater drilling operations, creating unexpected downtime and added risk. Deepwater operators on the OCS require accurate prediction on the LC and LCE location, intensity, and migration at meso- and even smaller scales (100 m – 10 km). As oil and gas exploration and drilling moves into deeper waters, the urgent need for improved monitoring and forecasting continues to grow.

Monitoring and forecasting the LC frontal development and evolution depends on the accurate, timely collection of real-time observational data. While many aspects of the LC intrusion and eddy detachment and separation events are observable at synoptic scales in several remotely sensed fields such as sea surface temperature (SST) and sea surface height (SSH), these methods are frequently limited by atmospheric conditions, limited coverage, and sensor resolution, respectively. This problem becomes acute for obtaining reliable data on the mesoscale LCFEs. Extensive use of satellite-tracked Lagrangian drifters in conjunction with remote sensing data has proven a more reliable means to delimit the major circulation features. The variable duration of drifter residency creates gaps in coverage, sometimes at critical periods, that necessitates regular drifter replacement. Despite many advances in recent years, these methods provide only partial knowledge of the LC/LCE location, movement, and evolution of the frontal regions because information about the subsurface structure of these features is absent. Improved prediction of the LC behavior is gained though in-situ oceanographic measurements acquired at sufficient spatial resolution to form a comprehensive view of the LC system.

Long-range autonomous underwater gliding vehicles (AUGVs) offer a means to collect ocean data repeatedly, autonomously, and at a very low cost compared to conventional methods. They are a more cost-effective solution for data collection than vessel-based systems and can investigate larger scale phenomena than is possible with moored instruments. All gliders using buoyancy propulsion have gradual glide trajectories at shallow angles around 18° to 25° from horizontal. Because the glide angle remains very steep relative to the slopes of ocean properties (e.g., temperature isotherms), this permits collection of the familiar cross-sections of temperature and salinity. Data collection proceeds continuously and can be transmitted in all but the worst of weather conditions. A glider's endurance, autonomy, and economy make it an ideal platform for gathering oceanographic data from the deepwater interior GOM. These data can be exploited for use in ocean monitoring and prediction systems.

Operational Program

In 2009, HMI began experimenting with using gliders for commercial monitoring of the GOM circulation in support of deepwater exploration and production. The HMI glider instrument facility is located in Houston, TX, and flight operations are conducted remotely from Marion, MA. All vehicle service and pre-deployment activities are completed in Houston, and we utilize Louisiana Universities Marine Consortium (LUMCON) for glider deployments. Two glider models with different systems and control architectures were used during the experimental phase. As of 2013, operations have been conducted using Slocum gliders manufactured by Teledyne-Webb Research. The development of physical facilities and technical capacity to work with gliders followed a phased approach, building on existing space, equipment, and skills. We developed protocols for data processing, storage, sharing, and visualization that take maximum advantage of existing capabilities. Our operational and piloting capacity was also built progressively, starting with short deployments and moving toward longer, more complex campaigns. This path was only partly by design. We were challenged by mistakes and occasional failure. Sustaining glider observations demands focus that competes with other staff responsibilities and practical realities intervene, such as weather and vessel availability.

Despite the label "autonomous", ocean gliders and most unmanned marine vehicles seldom operate in a fully automated capacity. A generic glider exercises control over its dive trajectory and gathers enormous volumes of data but lacks sophisticated algorithms to process the information and act intelligently on the results. Even so, operating gliders demands few man-hours relative to equivalent operations conducted using vessels. Most man-hours are committed to vehicle preparation, deployment, and recovery. Effective flight operations depend on assembling a situational awareness of the "ocean space" in which the glider operates. For 30 years, Horizon has focused on daily monitoring and prediction of GOM circulation by using observational data from satellites, Lagrangian drifters, and advanced 3D ocean forecast models. The glider data are easily integrated and visualized with these existing observations **(Figure 1)**. These real-time fields and analyses are then used by pilots for glider navigation and mission planning. Glider missions are adapted as needed to fill data gaps, repeat a route, or approach new targets of interest.

Glider endurance depends on micro-managing total power consumption (e.g., reducing data payloads, optimizing flight performance, or shutting off unnecessary devices). Typical battery usage is 4 Amp-hr per day and allows endurances > 130 days. Adverse currents exert a major influence on a glider that averages a speed of 0.5 knots (0.26 m/s) over ground. In the GOM, the strongest ocean currents are found in the upper 300 m, associated with the powerful Loop Current. Using simple strategies such as limiting the ascent altitude, we have successfully piloted gliders "upstream" for short distances against the prevailing > 3.0 knot (1.5 m/s)

LC. Conversely, favorable currents provide a substantial boost in forward speed.

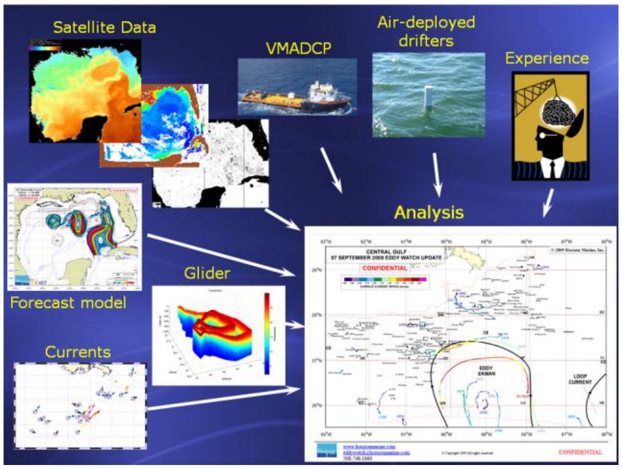

Figure 1. Aggregated data used for real-time monitoring of Gulf of Mexico circulation.

Operational Challenges

Operational challenges in the Gulf of Mexico arise from industrial, commercial, and recreational uses. With several major ports serving commercial shipping and the offshore petroleum industry (such as New Orleans, LA, Galveston, TX, Houston, TX, Mobile, AL, Port Arthur, TX, and Fourchon, LA), as well as numerous fishing fleets, vessel traffic is a major concern. In addition, the northern Gulf of Mexico has over 4000 drilling and production platforms, and large regions of the continental slope are seismically surveyed by multi-vessel fleets each year. Where high traffic regions cannot be avoided, the contact risks are diminished by minimizing glider surface time.

The list of challenges includes problems encountered with glider hardware, software, shore-side communications, server failures, and mother-nature. To their credit, glider manufacturers have worked hard to eliminate known hardware and software problems. Major failures have been self-inflicted due to inadequate preparation or mistakes. While major failure modes can be anticipated and mitigated through careful pre-deployment planning (leaks, wing loss, pump problems, device failure), some unexpected risks arise from poor piloting decisions. Other avoidable risks stem from the compounding of minor technical problems that eventually endanger the mission or the vehicle and require intervention. In our experience, this “snafu-time” scales at 1-2% of the total deployment hours--e.g., during a 2000-hour deployment, a pilot should anticipate between 20 to 40 hours for diagnostics and corrective.

Mother Nature presents unexpected challenges due to weather and biological interference. Prolonging surface time while performing shallow dives, holding station, or drifting will lead to increased biofouling. Continued cycling from the surface to the cold, dark, high-pressure environment at 1000 m is hostile to most organisms and practically eliminates biofouling altogether. Uninvited biological interference remains a concern, whether from humans or large oceanic nekton. For example, during a dive on March 12, 2013, a glider suddenly rolled to 30°, pitched nearly vertical to 70°, and descended 6 m in 10 seconds. The subsequent vehicle attitude and rate of ascent indicated a mass deficit of nearly 90 gm, consistent with the partial loss of the port wing. Fortuitously, only minor impacts to speed or control were noted for the remaining 3 months of the deployment. Examining the recovered wing-stub showed that the wing had been sheared off with no evident damage to the glider hull. The glider was operating in deep blue tropical waters, known to host large, aggressive predators, but no cause can be certain.

Observations in the Gulf of Mexico

Glider deployments are generally focused on surveying the central and eastern GOM, from the northern GOM slope to as far south as Cuba and the Yucatan Channel. Deployments are generally 120 days, span distances of 2500 km, and collect 1000 CTD profiles to 1000 m. In rough total, we have accumulated over 7400 km, 365 glider days, and more than 3000 profiles since 2011. Even with slow speeds, a glider can complete a north-south cross-section from the northern GOM slope to Cuba and cover 625 n.mi. (1157 km), passing through the major mesoscale feature of interest including the NGOM front, Loop Current, Loop Current Eddy, Loop Current Frontal Eddy, and Yucatan Channel inflow in less than 40 days. With long deployments that span a significant portion of the Loop Current’s eddy shedding cycle (8-11 months), a single glider can revisit major mesoscale features and track their interior evolution.

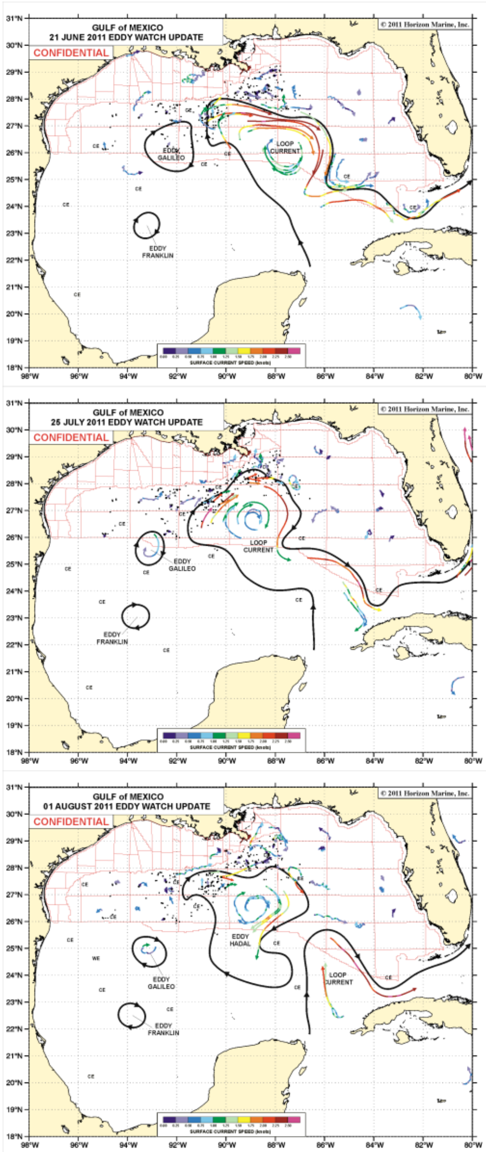

Figure 2. Sequence of LC activity during 2011: spawning of Eddy Galileo on 21 June (top), incursion of the LC to latitudes > 28.5°N on 28 July (middle), and shedding of Eddy Hadal by 30 July (bottom).

As an example of this, we describe the oceanographic data collected during a glider survey conducted from April to August 2011, covering a linear distance of 1400 n.mi. (2700 km) and comprising 1000 vertical profiles. Cross-sections of water properties were obtained throughout the upper 1000 m with 2.5 m vertical resolution. The 112-day deployment (14 April to 03 August) spanned a period of intense activity by the Loop Current (LC). The LC invaded northern Mississippi Canyon, reaching latitudes north of 28.25 °N, and spawned two eddies - Eddy Galileo on 21 June 2011 and Eddy Hadal on 01 August 2011 (**Figure 2**). During this period, the glider obtained several cross-sections through the LC front and several cyclonic frontal eddies and operated in close proximity to deepwater platforms on the NGOM slope (**Figure 3**). From the cross-sections of temperature, salinity, and density, we can derive the geostrophic velocity due to differences in geopotential anomaly between adjacent profiles. The depth averaged velocity reference can be calculated directly from the difference between the glider dead-reckoned and GPS positions following each dive. With these data, we can produce useful maps of the LC velocity cross-section down to 1000 m.

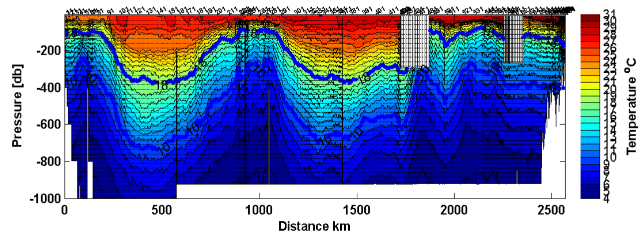

Figure 3. Glider cross-sections of temperature obtained during through the mesoscale features in Figure 2 from April to August 2011.

Major water masses encountered by the glider during this period are identified in the inset of **Figure 4**. Outside the LC and in the upper water column below the mixed layer, the glider encounters water with the characteristics similar to Gulf Common Water (GCW). Inside the Loop Current is found the Subtropical Underwater (SUW, also known as Tropical Water) which is characterized by a pronounced salinity maximum (Rivas, et al., 2005). At intermediate and greater depths (> 200 m), the glider encountered transitional water sometimes referred to as Tropical Atlantic Central Water (TACW). At depths below 800 m, there is a salinity minimum (S< 34.8, T=6 °C) which is associated with Antarctic Intermediate Water (AAIW). Water properties at 800-1000 m are largely stable and provide a useful standard for calibrating the glider CTD.

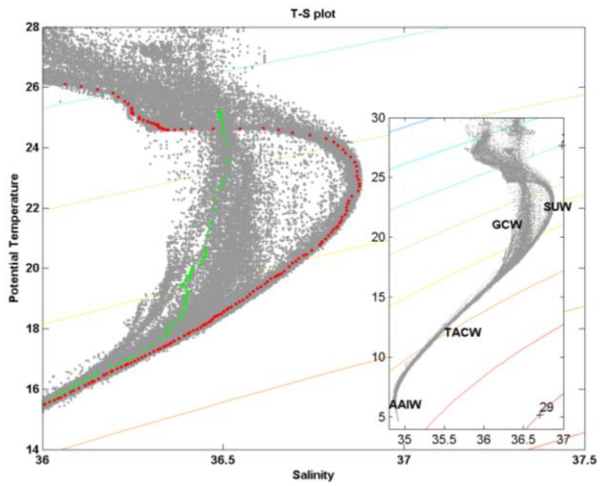

Figure 4. T-S plot of glider data between April and August 2011 (gray dots). Major water masses are identified in the inset figure.

As the glider penetrates into the LC front, the boundary region between the exterior and tropically-derived LC water mass can be visualized from the location and depth of the 18 °C isotherm (**Figure 5** and **Figure 7)**. The 18° isotherm plunges from 100 m to 320 m over an along-track distance of 170 km (92 n.mi.). Isopycnals throughout the upper 1000 m are perturbed. The pycnocline subducts along the track and is tilted steeply between 190-200 km along the track and above 150 m. Inside the LC front, the T-S profiles reflect the distinct presence of the SUW. Inside the LC, the surface mixed layer (100 m thick) consists of relatively fresh (35.75 PSS) and relatively warm (> 28 °C) tropical surface water. The surface temperatures of this upper layer vary seasonally. The SUW water mass with maximum salinities (36.8 PSS) is forced beneath the low-density warm tropical surface waters in the LC. The LC current magnitudes (> 3.5 knots, 1.8 m/s) are most intense in the region of strongest horizontal and vertical gradient (**Figure 6**).

A second cross-section through the LC was performed about one month later through the western boundary of the LC on 24-31 May (**Figure 7**). The LC position had advanced north and west by this time, just prior to detaching as Eddy Galileo on 21 June. The glider was directed to enter the LC from its west side, passing through an LCFE and into the LC interior. The tilt of the isotherms at the beginning of the section indicates the edge of the LCFE along the western (cyclonic) side of the LC. Surface waters of the LC exceed > 29 °C by May. The steep LC front is indicated by the 18 °C isotherm which dives from 100 – 325 m over the course of 250 km (134 n.mi.). The maximum current in the upper 50 m exceeds 3.5 knots (1.8 m/s). The maximum current diminishes to < 1.0 knot (0.51 m/s) by 400 m. A weak counter flow appears below 600 m (< 0.5 knots, 0.25 m/s) directly under the LC core.

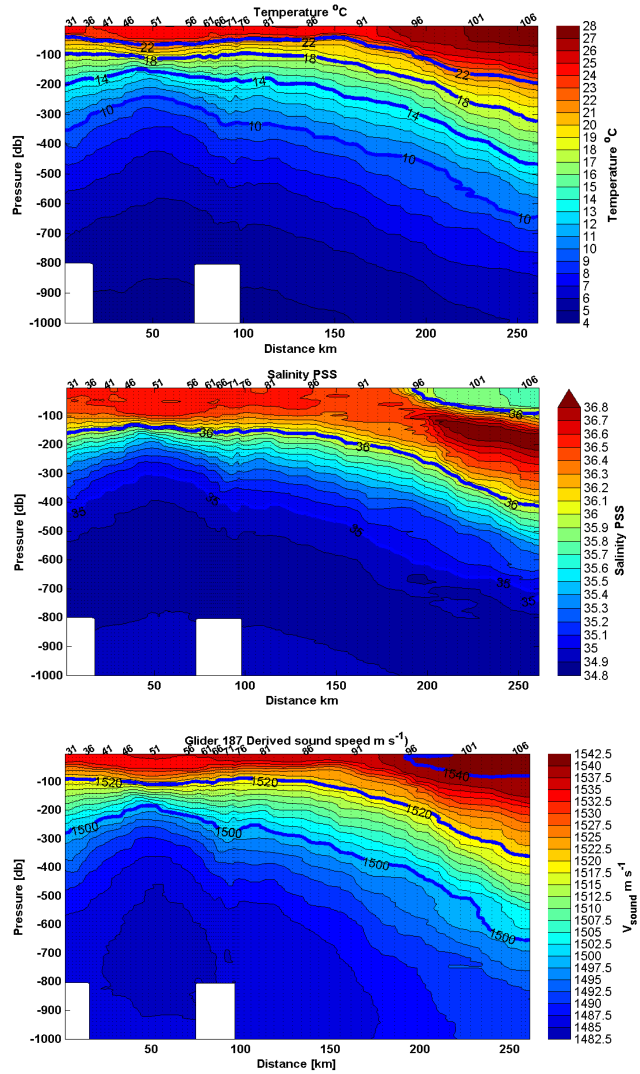

Figure 5. Cross section from 17-29 April from the NGOM slope into the LC front region: temperature (top) and salinity (middle), sound velocity (bottom).

Cyclonic LCFEs have cold cores which are regions of vigorous subsurface upwelling that produces doming of cool water. These vortices are often located along the cyclonic side of the Loop Current. The presence of cold-core cyclones are indicated by upwelling of the 10 °C isotherm by > 100 m over the first 100 km of the cross section in **Figure 5**. The LCFE cyclonic flow approaches > 0.5 knots (0.25 m/s) over the upper 400 m and a band of higher speed > 1.0 knot (0.51 m/s) at a radius of 40 km (21 n.mi.). One interesting consequence of the upwelled density structure within the LCFE can be seen in its effect on sound velocity in **Figure 5**. The upwelled isotherms and isohalines result in a relative minimum in the sound velocity centered at depths between 500-900 m. Such measurements in LCFEs are valuable because their vertical structures are chronically misrepresented in most numerical models of the GOM circulation. Concurrent trajectories of satellite-tracked drifting buoys passing near the region are generally consistent with current magnitude observed in the LC front (**Figure 8**).

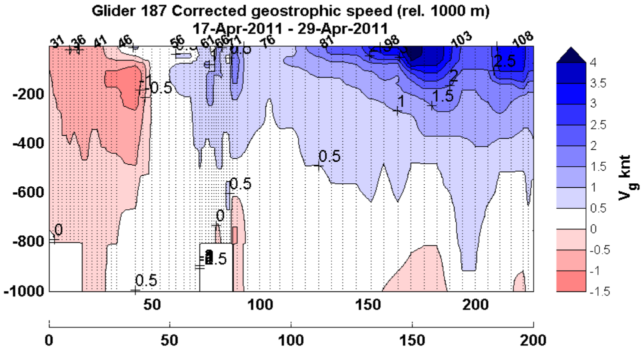

Figure 6. Geostrophic velocity relative to 1000 m vs. distance in km based on data in Figure 5.

Forecast Models

The primary consumers of glider data are high-performance ocean models. Model performance and forecasting skill greatly benefit from high resolution density profiles needed to fully describe the 4D structure of dynamic meso-scale structures. Since 2004, Horizon has utilized a proprietary forecast system (Coholan, et al. 2005) that has been running operationally in partnership with Weather Predict Consulting. The system uses an existing high-performance, high-resolution ocean model for the prediction component combined with a completely unique, feature-based initialization component. This is analogous to "vortex bogusing" used so successfully in hurricane forecasting (Robinson and Gangopadhyay, 1997). The prediction component of the EFS uses the parallelized version of the MIT ocean model (Marshall, et al. 1997) configured for a spatial resolution of 4 km and runs on a cluster of 72 computing nodes. The initialization component unites observational data from a variety of sources (including glider profiles) to formulate a nowcast of existing conditions pertaining to the features of interest. Direct incorporation of glider profile data leads to a substantial reduction in the interior density error field and improved forecasting skill and forecast horizon (**Figure 9**).

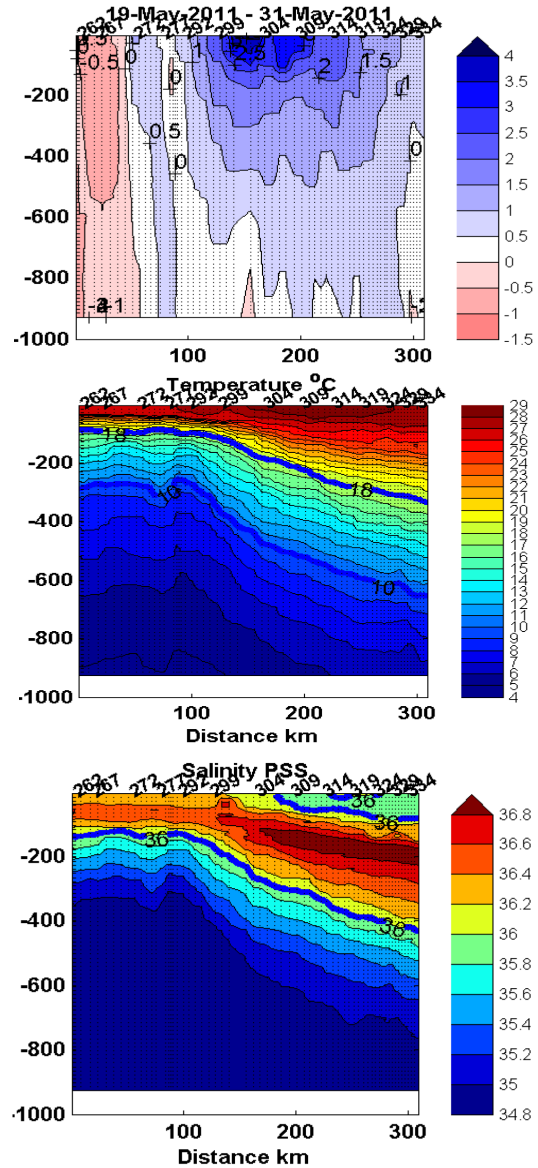

Figure 7. Cross-section from 24-31 May extending from west to east into the LC front region: velocity (top), temperature (middle), and salinity (bottom).

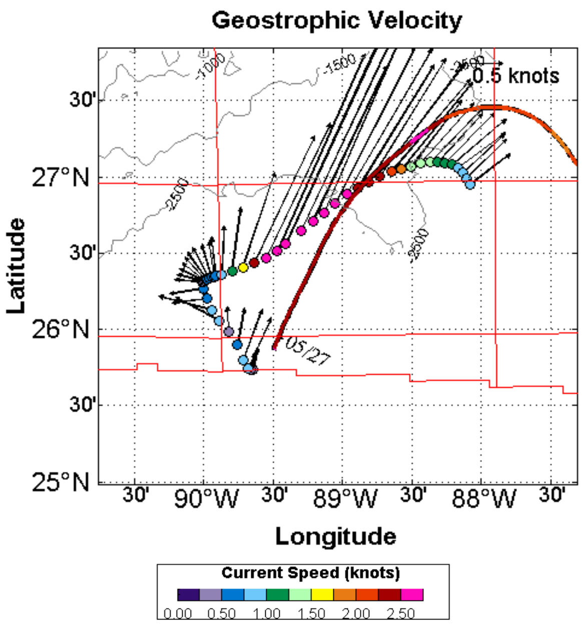

Figure 8. Glider position and geostrophic velocity at 25 m from 24-31 May. The trajectory and speed of drifter #2727 is overlaid for the period 27-31 May.

Summary and Conclusions

The GOM circulation is dominated by the LC and its associated eddies which greatly influence circulation over the upper NGOM slope and shelf. Deepwater operators have long recognized the importance of monitoring the LC to maximize safe and efficient operations. Today the GOM is among the most highly sampled and monitored deep ocean bodies in the world. Even so, the detailed knowledge about the 4D structure and intensity of the LC remains unobserved over large portions of the region through which it passes. Gliders, or AUGVs, provide a means for sustained measurement of the LC over much of this domain. Glider technology has a long track record in the research community and is now part of sustained ocean observations in many regions (Todd, et al., 2011). Commercial adoption of this technology is now possible. As we have shown here, gliders reveal details of the LC subsurface structure and provide a means to monitor the evolution of the interior density structure as it matures and sheds eddies. Such subsurface measurements also capture details about smaller meso-scale features that lie in close proximity to the LC and will ultimately result in improved forecasting.

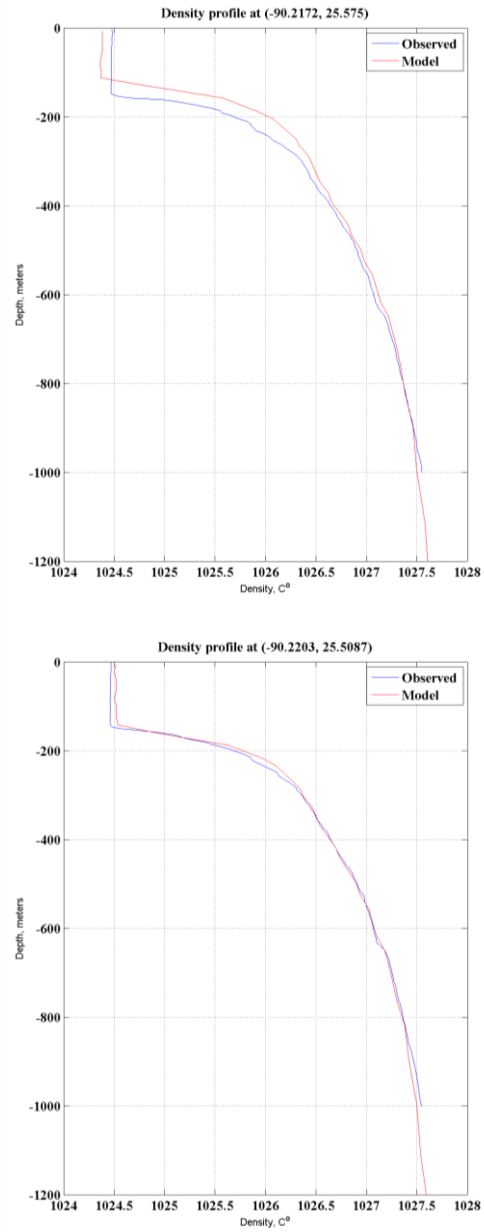

Figure 9. Model density profiles compared with glider data before data assimilation (top) and after (bottom).

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